

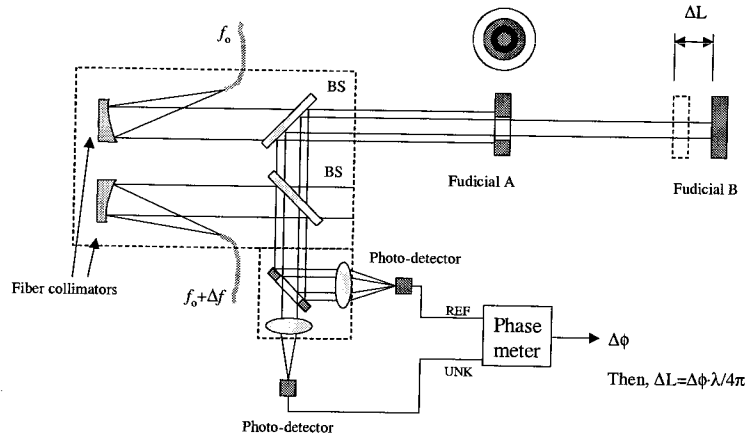
# DEMONSTRATION OF SUB-ANGSTROM CYCLIC NONLINEARITY USING WAVEFRONT-DIVISION SAMPLING WITH A COMMON-PATH LASER HETERODYNE INTERFEROMETER

Feng Zhao

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Several NASA's missions such as the Space Interferometry Mission, call for a displacement measuring interferometer (DMI) with a linear accuracy better than 0.1nm. Traditional implementations of DMI are based on laser heterodyne techniques and polarization to separate and combine the measuring beams. However, traditional interferometers suffer from periodic nonlinear errors on the order of a few nanometers due to optical self-interference. Polarization leakage has been found to be the dominant source for the periodic nonlinear error. With even state-of-the-art polarizing optics, the nonlinear error is still difficult to be reduced to less than 1nm. In addition to having large nonlinear error, traditional DMIs are quite sensitive to temperature changes and are far-off from meeting the stability requirement imposed by these proposed missions.

A novel common-path heterodyne interferometer (COPHI) was proposed at JPL as a multi-purpose, high resolution laser interferometer [1-2]. In this paper, we describe a new approach to address both the cyclic error and thermal stability problems. Figure 1 shows the schematic of COPHI configured as a displacement measuring interferometer. Figures 2 and 3 show the pictures of the prototype COPHI we have developed at JPL.

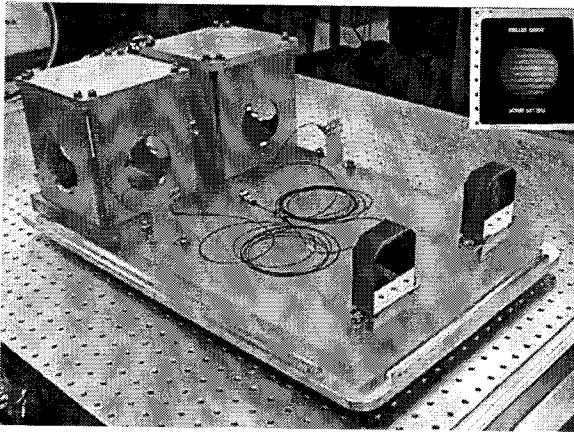


**Figure 1. Schematic of a common-path heterodyne interferometer, configured for displacement measurement.**

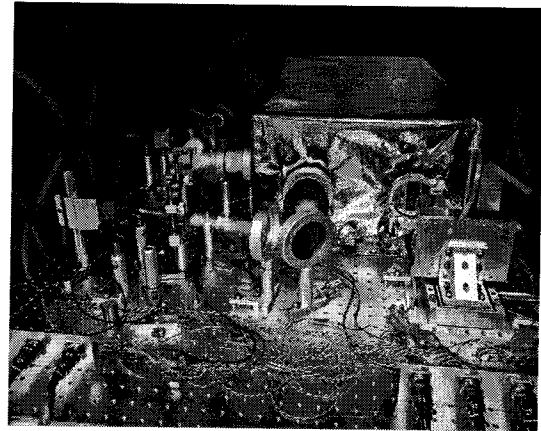
In this interferometer, both the measurement and reference beams are collimated from a pair of polarization-maintaining fibers with two Zerodur off-axis parabolic mirrors. In the displacement measurement configuration, we use a flat mirror with a center hole as fiducial (A) and a second flat mirror as fiducial (B), as shown in Figure 1.

The center hole in fiducial (A) allows the center portion of the beam at frequency  $f_o$  to reach fiducial (B). This way the measurement beam  $f_o$  is split into two symmetric sections. Both mirrors are aligned to retro-reflect the beams back to the interferometer to combine with reference beam at frequency  $f_o + \Delta f$ , which serves as a local oscillator. At this point, two interference fringes are formed, the annular fringe formed by fiducial (A) and the center fringe formed by fiducial (B). Then the heterodyne fringes are spatially separated with a truncated mirror and focused into separate photo-detectors. The phase difference ( $\Delta\phi$ ) between the reference and measurement signals is then used to calculate the displacement ( $\Delta L$ ) between the fiducials:

$$\Delta L = \Delta\phi \frac{\lambda}{4\pi}.$$



**Figure 2 .** Picture of the collimator/beam-splitter assembly. They are mounted on a Zerodur plate to ensure good thermal stability. The beams are 50mm in diameter and the shear interference fringes (top right) show the wavefront quality is better than  $\lambda/5$  P-V for both beams.

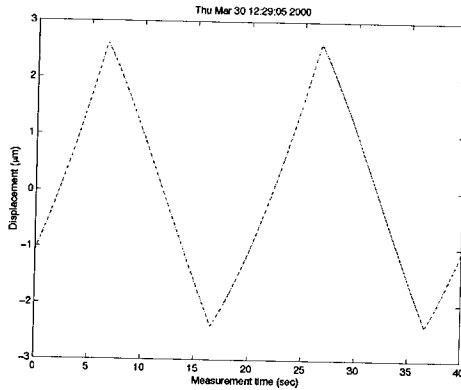


**Figure 3.** Picture of the interferometer. The collimator/beam-splitter assembly is covered with multi-layered insulator (MLI) to isolate the optics from the ambient temperature fluctuations. The heterodyne beams are generated with two acousto-optic modulators with their RF frequencies separated by  $\Delta f=10\text{kHz}$ .

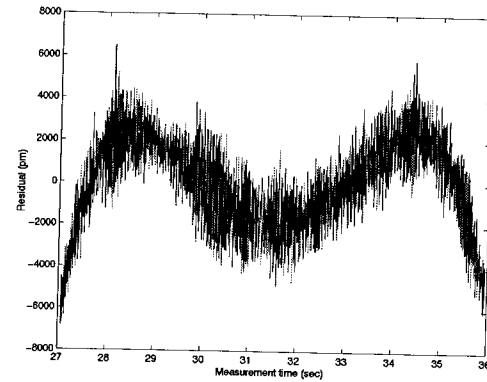
To measure the residual periodic nonlinear error, a PZT is used to translate fiducial (B) “linearly” over a distance of many laser wavelengths. The distance is then measured with a phase meter. A periodic error in this “linear” translation can be estimated by looking at the power spectral density of the displacement data. In our experiment, the laser wavelength is  $0.532\mu\text{m}$ , and the total stroke of the PZT is about  $5\mu\text{m}$  with a triangle wave modulation at  $0.05\text{Hz}$ . Thus cyclic error with  $\lambda/2$  periodicity can be found at about  $2\text{Hz}$  in the spectral domain.

Figure 4 shows the measured displacement of the PZT. We select an arbitrary linear displacement, e.g., between 27 and 36 seconds in Figure 4 for analysis. Figure 5 shows its residual after removing its linear to cubic terms. The power spectral density of the residual is calculated and plotted in Figure 6, in which the peak at  $2\text{Hz}$  indicates the existence of  $\lambda/2$  periodic nonlinear error. The total energy of this cyclic error is estimated

to be about  $730\text{pm}^2$ , which translates into a periodic nonlinear error of only  $27\text{pm}$  RMS. This result represents a roughly 100 times improvement over traditional DMIs.

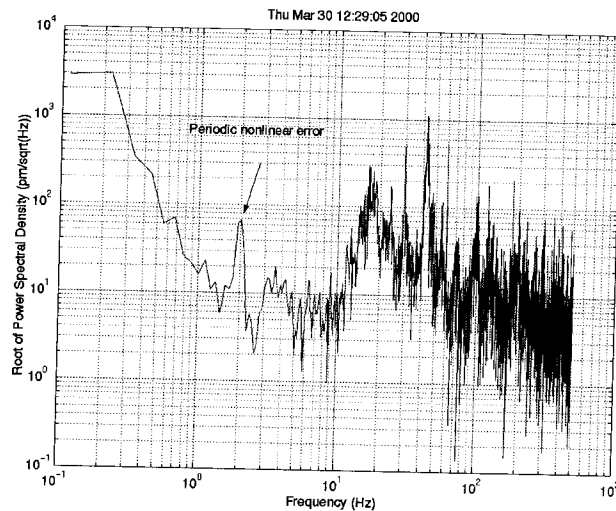


**Figure 4 . Displacement of the PZT measured with the interferometer.**



**Figure 5. Residual of the displacement between 27 and 36 seconds after removing its linear to cubic terms.**

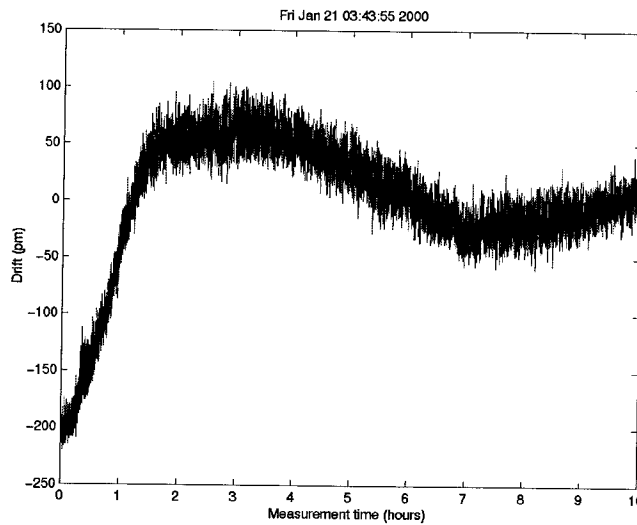
This implementation of the DMI eliminates once the largest error source, i.e., polarization leakage. Nevertheless, several other sources such as ghost reflections, diffraction induced cross-talk between the two measurement beams can still cause self-interference thus periodic nonlinear error. In the above proof-of-concept demonstration, we use a guard-band between the two measurement beams to lower the diffraction cross-talk. The beam splitters have a small wedge and good anti-reflection coatings are applied to the back surfaces to minimize the effect of ghost reflections. The  $27\text{ pm}$  periodic nonlinear error may be attributed to diffraction and ghost reflections in the interferometer.



**Figure 6. Power spectral density of the displacement data. As the PZT moves "linearly", the periodic error distinguishes itself from the noise background in the spectral domain. This result indicates a cyclic error of about  $27\text{pm}$  RMS. Background noise measurement with PZT driver off indicates that peaks above  $10\text{Hz}$  are attributed to vibrations in this setup.**

It should be noted that in COPHI, the two measurement beams (annular and central) are derived from the same wavefront using wavefront-split approach. In other words, thermal expansion of the optical components in the interferometer is common-mode. This feature greatly improves the temperature stability of the interferometer.

In the thermal stability measurement, we replace fiducials (A) and (B) with a single Zerodur mirror. This single mirror ensures that there is no change in the fiducials during the measurement. Changes of the phase between the annular and central fringes are due to the drift of the interferometer itself. Figure 7 shows a measurement of the drift over 10 hours. The result indicates that the interferometer is stable to better than 100pm over 1 hour period.



**Figure 7. Stability measurement of the interferometer. The drift is less than 100pm over 1 hour period.**

In this paper, we proposed and demonstrated a novel displacement interferometer with extremely low periodic nonlinear error ( $\sim 27$ pm RMS) and ultra high temperature stability (better than 100pm over 1 hour). These results represent more than an order of magnitude improvement over traditional interferometers. In addition, this interferometer is simple and quite easy to implement. It may find wide applications in a variety of ultra-high precision measurement ranging from atomic force microscope calibration to gravitation wave sensors, etc.

The author would like to thank Robert E. Spero for his help on data analysis. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

#### REFERENCES:

- [1] F. Zhao, "A common-path, multi-channel heterodyne interferometer," NASA Tech. Briefs, Vol. 25, No. 7, pp12 (2001).
- [2] F. Zhao, J. Logan, S. Shaklan, and M. Shao, "A common-path, multi-channel heterodyne laser interferometer for sub-nanometer surface metrology," SPIE Proceedings, Vol. 3740, pp 642-645 (1999).